IDRC-TS9e

Remote Sensing in the Sudan

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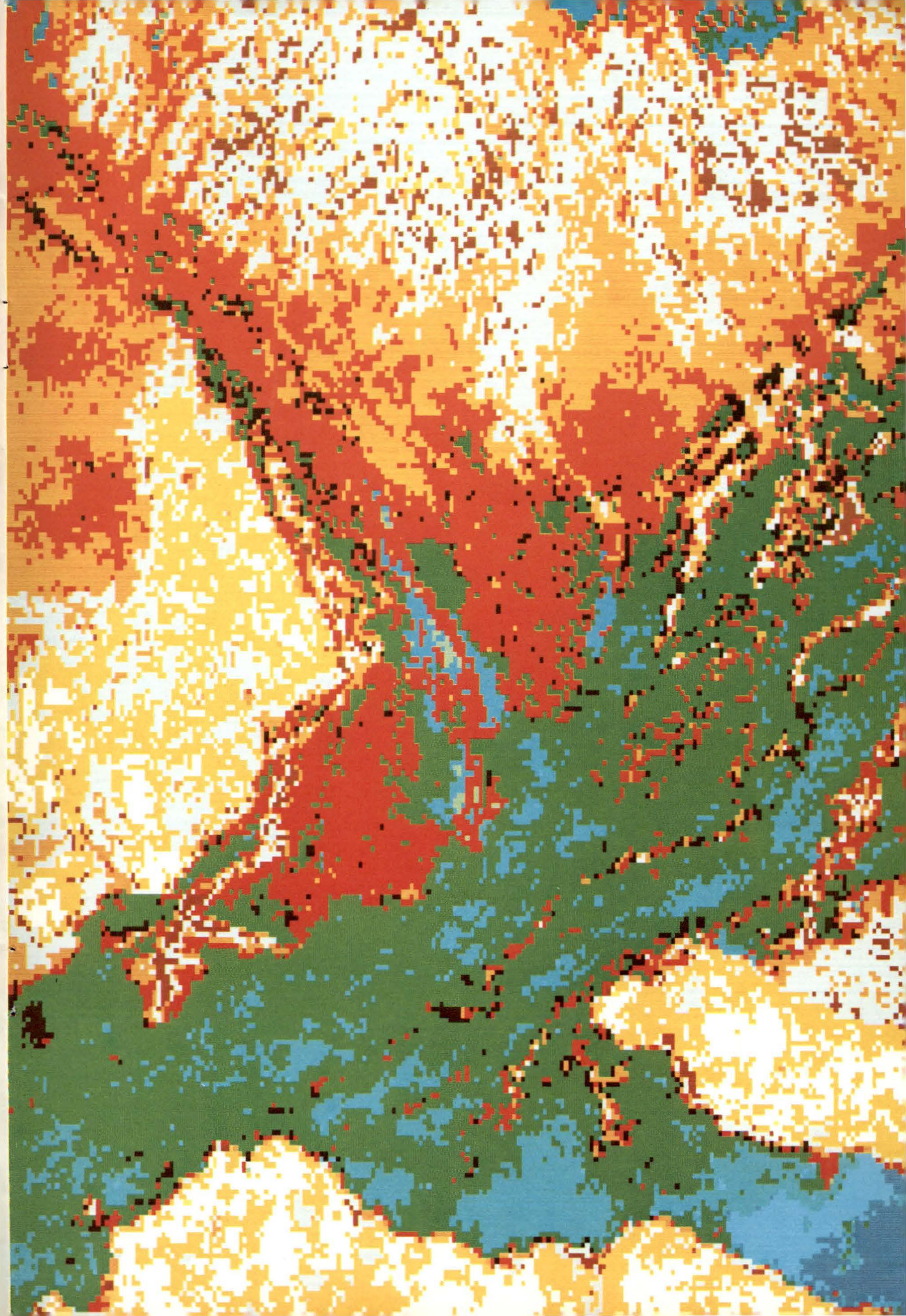

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Remote Sensing in the Sudan

Hassan El Sheikh El Bashir, Yahia I. M. Bushara, Yousif Yagoub Mohammed, El Mardi Ahmed Hassan, Khalid Ahmed Khalil Ibrahim, and Abdel Rahim Abdel Aziz Mohammed
(Participants in a remote sensing pilot project)

Frontispiece: Colour-coded classification (reduced to approximate scale of 1:65 000) of area along Khor Abu Habl between Jebel Ed Dair and Turda Er Rahad produced by computer-implemented analysis at LARS of MSS data from Landsat-1 pass, 8 November 1972 (see Table 10, page 29, for key to colour classes).

Contents

Foreword

This book describes one of a series of five projects in which IDRC is helping developing countries build their capacities to exploit satellite remote-sensing (Landsat) data for thematic cartography. The geographical diversity of the locations (Sudan, Bolivia, Tanzania, Mali, Bangladesh) should lead to the development of a useful set of reference criteria for other developing countries wanting to adapt Landsat technology to their needs.

In each of the projects, a similar research approach was taken, with priority being given to the preparation of thematic maps on geology, water, soils, vegetation, and land uses. A multidisciplinary team of local scientists, under the guidance of a consultant, made a preliminary analysis of Landsat data, and conducted a field study of the project area. This was followed by a training course for the project team on methods of analysis of the Landsat data. After verification of the compiled data by a second field inspection, thematic maps of the area were produced.

The Democratic Republic of the Sudan was one of the first African countries to take advantage of NASA's offer in 1971 to supply Landsat data and images to interested researchers. In 1972, Sudanese government authorities and scientists formed an interdepartmental committee to plan the creation of a remote-sensing applications unit. The question arose as to how this research facility would be able to respond to the needs of the various ministries and planning agencies. There were two priority areas: the training of Sudanese researchers, and applied research. Since IDRC was also interested in the application of Landsat technology, a cooperative research project was designed with the Sudan Ministry of Agriculture, Food and Natural Resources based on a detailed planning document drafted by the Sudanese interdepartmental committee. Thus emerged the Sudan Remote Sensing Pilot Project, which was executed by the Remote Sensing Unit of the Ministry's Soil Conservation, Land Use and Water Programming Administration.

This project is one of the first in a series of IDRC-supported remote-sensing projects. We in the Centre have been honoured to cooperate with the Democratic Republic of the Sudan and now we have the satisfaction of seeing the accomplishments of the Sudanese research team recognized in the establishment of a permanent remote-sensing unit.

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Acknowledgments

The financial support given by the International Development Research Centre (IDRC), Canada, which strengthened the Remote Sensing Unit and enabled it to execute this project, is appreciated.

We also wish to express our gratitude and thanks to members of the staff at the Laboratory for Applications of Remote Sensing (LARS), Purdue University, and particularly Ms Tina K. Cary, Training Coordinator, and Prof M. F. Baumgardner for his assistance during the project and in the publication of this report.

Thanks are also extended to members of the staffs of the Earth Resources Observations Systems (EROS) Data Center, the Goddard Space Flight Center, and the Canadian Centre for Remote Sensing for their help and advice.

Introduction

Early in 1971 the Food and Agriculture Organization Near East Office informed the Government of the Democratic Republic of the Sudan that in cooperation with the National Aeronautics and Space Administration (NASA), FAO had chosen the Sudan and two other countries in Asia and South America as test areas for the possible utilization of remote sensing for resource surveying, mapping, planning, and development. The Council of Ministers in the Sudan agreed to the proposal after being convinced of the many advantages and benefits that the country would gain from this new technology.

The Sudan is a vast and expansive country with limited technical and financial resources, but with many climatic and ecological zones, extending from the desert in the north to the tropical forests in the extreme southwest. Thus, it would be impractical from technical, economic, and time considerations to rely on using ordinary aerial photography for resource surveys of the country's more than 2.5 million square kilometres.

The area selected for the remote-sensing pilot test was located within the savannah belt between latitudes 10°00'N and 14°00'N. In 1972 the Sudan Government, in cooperation with FAO, was carrying out the Savannah Development Project for reconnaissance of land and water resources in the southern part of this selected area. This meant that recent aerial photographs as well as foreign experts were available. Accordingly, FAO requested the project manager to ask some of the experts in the project to study the satellite images that had been obtained over part of the area by Landsat-1 during the period August 1972 to March 1973.

Correlation of ground observation data with features on both the Landsat images and the aerial photographs was made by the soil / geomorphology and the vegetation / range-management experts of the Savannah Project. Their report on the possible uses and limitations of satellite data was submitted to FAO headquarters.

In 1973 FAO hired Dr C. W. Mitchell from Reading University, U.K. as a consultant for one month to study this report, to conduct field trips to the area covered by the report, and to lecture and train Sudanese experts on the techniques of using remote sensing.

Prof M. F. Baumgardner was engaged by FAO in 1974 to study the previous reports, evaluate the results, and produce a project proposal that would enable FAO to help the Sudan make use of this new technology. The Ministry of Agriculture, Food and Natural Resources (AFNR) then approached the International Development Research Centre (IDRC) to ask for assistance in establishing a Remote Sensing Application Unit, to be located in the Soil Conservation, Land Use and Water Programming (SCLUWP) Administration, that would carry out resource surveys, mapping, and planning.

IDRC agreed in 1975 to grant the SCLUWP Administration of the Ministry of AFNR approximately $181 000 to establish this Remote Sensing

Application Unit. This grant was to be used for the training of an integrated team of six Sudanese scientists in the digital analysis of Landsat multispectral data and for the purchase of laboratory equipment for the Unit. The training took place at the Laboratory for Applications of Remote Sensing (LARS), Purdue University, Indiana, USA under the supervision of Prof Baumgardner.

Pilot Project

The project area lies within the savannah belt of the Sudan, covering parts of Northern Kordofan, Southern Kordofan, and White Nile Provinces. Bounded by longitudes 29°40'E and 33°14'E and latitudes 12°00'N and 13°05'N, the area is covered by parts of five Landsat-1 frames (Fig. 1).

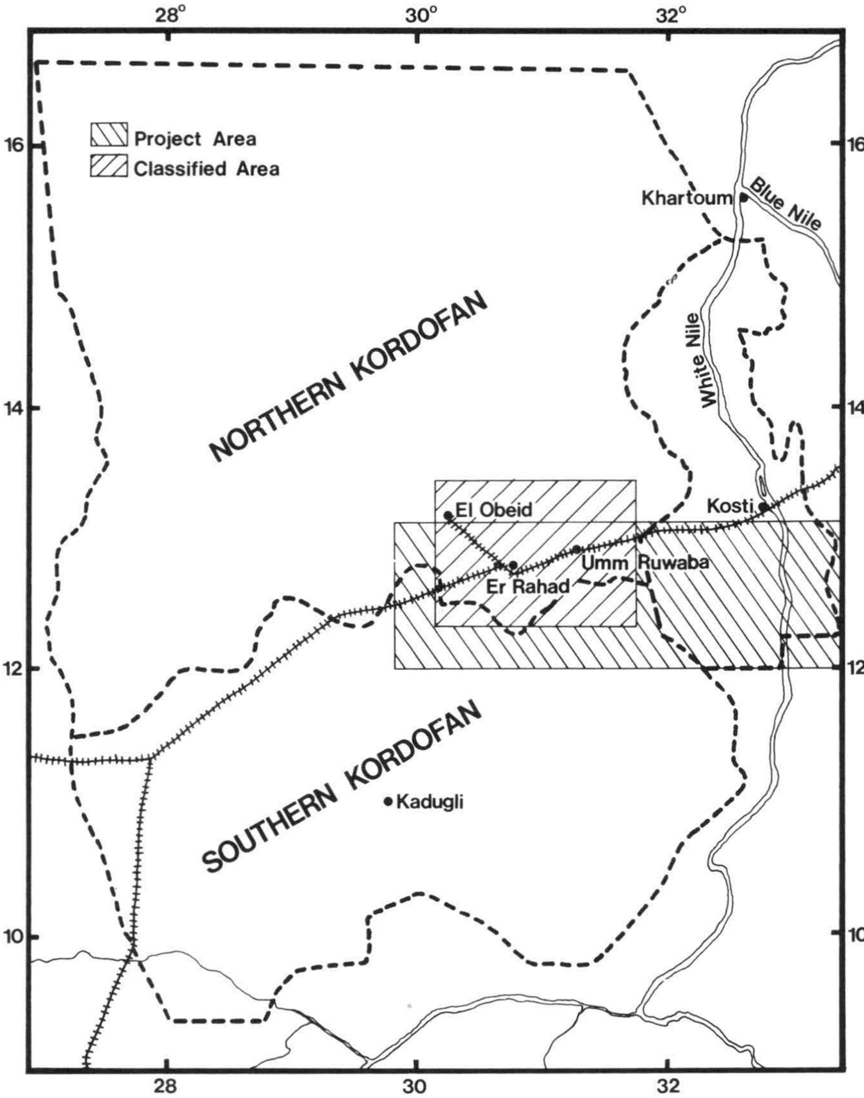

Fig. 1. Location of development project area and classified area.

The plan was originally to classify the entire 50000 km^2, and accordingly, ground samples were taken for the whole area. However, actual classification at LARS covered only one Landsat frame (longitudes 30°01'E and 31°31'E, latitudes 12°21'N and 13°25'N). This reduction in area was dictated by the following constraints: (1) the training period was short; (2) a considerable amount of time at LARS was spent on studying the principles of remote sensing, which was essential for the training; and (3) most of the field samples were within this frame, which at the same time included most of the features in the area.

The reduced area that was classified covers approximately 20000 km^2. It is generally undulating and includes sand sheets and sand dunes in the northern and eastern parts. On the other hand, the southern part, which is separated by Khor Abu Habl (a seasonal stream), is a clay plain. It is in this plain that the Jebel Ed Dair (a granite hill) is situated. The two towns of El Obeid and Er Rahad fall north of Khor Abu Habl, as do three water reservoirs, namely Er Rahad Turda (pond), Banno reservoir, and El Ain reservoir.

The average annual rainfall in the area is about 500 mm. The vegetation is scrub forest and sparse grassland, with dense vegetation along water courses and inflow areas. Dryland farming or rain-fed cultivation, although found throughout the area, is mainly concentrated on the sands. The main crops are millet, groundnuts, sesame, and sorghum in rotation with gum arabic trees (*Acacia senegal*).

The main objectives of this project were: (1) to transfer new information technology to members of the Remote Sensing Unit through training and research; (2) to provide a high quality data base (Landsat imagery) for present uses and future reference; and (3) to produce maps of natural resources on a selected area of Sudan's savannah belt by using visual interpretation of Landsat false-colour imagery, and digital analysis of Landsat multispectral-scanner (MSS) data.

The project started in September 1975, after the signing, in June 1975, of the agreement between the Sudan Ministry of Agriculture, Food and Natural Resources, and the International Development Research Centre. Prof Baumgardner conducted the first field study and survey tour during the period 27 October to 9 November 1975, to familiarize the project personnel with the study area and to obtain ground observation data to serve two important functions: (1) as training sets for computer identification of features of interest; and (2) as test sample sets to evaluate the analysis results.

In addition to Prof Baumgardner the field mission included the following Sudanese scientists: Akasha Mohammed Ali a crop protectionist; Abbas Ballal a forest inventory officer; El Mardi Ahmed Hassan a geologist; Khalid Ahmed Khalil Ibrahim a soil surveyor; Abdel Rahim Abdel Aziz Mohammed a hydrologist; and Yousif Yagoub Mohammed a soil conservation and land use officer. During the mission the project area was traversed from the extreme west to the extreme east. More traverses were made to the north and south of Er Rahad and Umm Ruwaba, and to the south of Kosti. In all, data were collected from 33 observation points.

The spectrally separable features of the false-colour prints were located on the ground by using 1:250000 scale topographic maps and aerial-photo mosaics of 1:50000 scale that covered part of the area. At each observation point, data related to the following subjects were collected: geomorphology and soil, soil erosion, hydrology and surface drainage, land use, geology, and type of vegetational cover.

After the trainees returned to the Sudan, geometrically corrected black and white images of the project area were produced on an electronic printer / plotter at LARS. Images at the approximate scale of 1:120000 were produced for Landsat MSS bands 4, 5, and 7. These images proved to be very useful in estimating distances and in delineating broad categories of soils, communities of vegetation, types of land use, towns and villages, drainage patterns, and geological features.

One of the interests of the Sudanese scientists was to consider the different kinds of hardware and equipment currently available for image production, and the analytical products that could be obtained from Landsat MSS data. One method of displaying multispectral data is through a digital image display. Black and white images were produced from each of the Landsat MSS bands for the project area (Fig. 2-5). A visual examination of these images revealed that the boundaries between sandy soils and the eroded upland clays were difficult to establish in band 4 (0.5-0.6 μm). In each of the other bands, however, the delineations were easily made. In addition, band 7 (0.8-1.0 μm) seemed superior for delineating some of the differences in vegetation complexes, especially in the flood plains.

The digital image display, which is a high resolution television tube, is a useful tool for displaying digital data in an image format. However, it provides an image that lacks sharp, crisp definition, and the device introduces geometric distortion into the photographs of the images (Fig. 2-5).

Band 6 (0.7-0.8 μm) was selected for a comparison of two black and white images that were at essentially the same scale but had been prepared by different methods. These two images (Fig. 4 and 6) covered much of the same area along the Khor Abu Habl. The image in Fig. 4 was prepared by taking a photograph of the image on the television screen; the image in Fig. 6 was

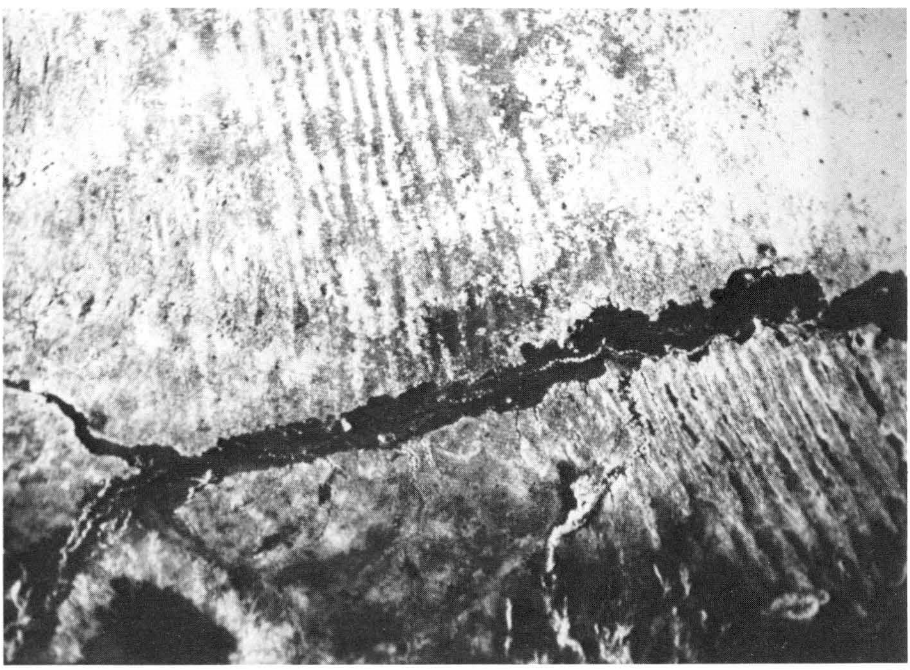

Fig. 2. Image of project area produced on digital image display from Landsat MSS band 4 data.

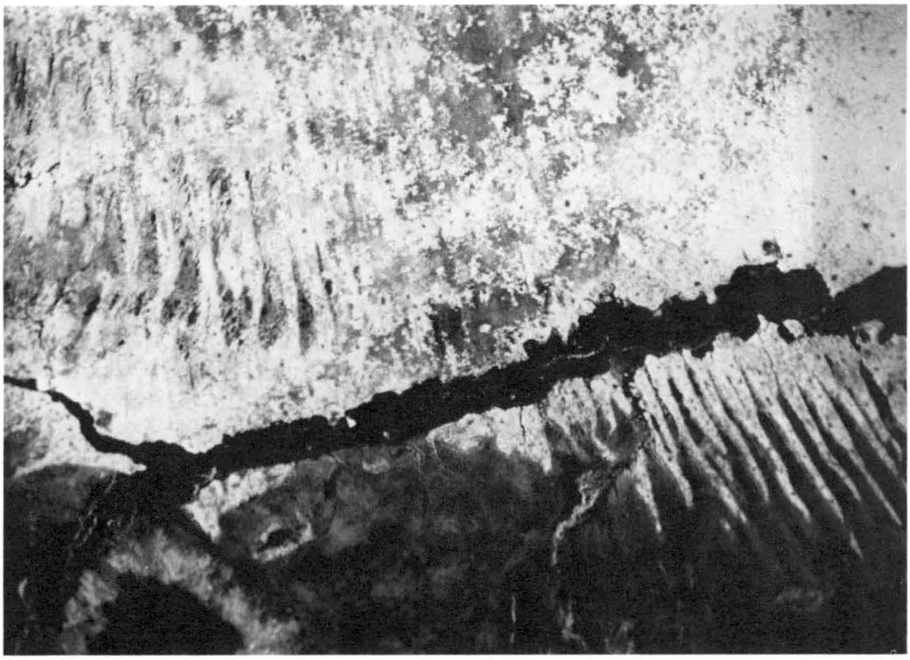

Fig. 3. Image of project area produced on digital image display from Landsat MSS band 5 data.

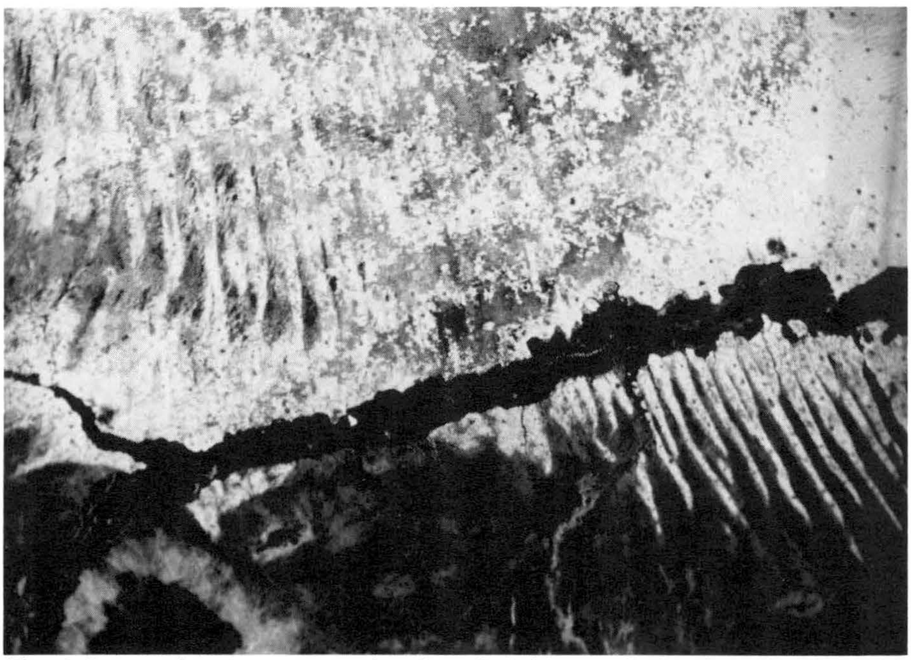

Fig. 4. Image of project area produced on digital image display from Landsat MSS band 6 data.

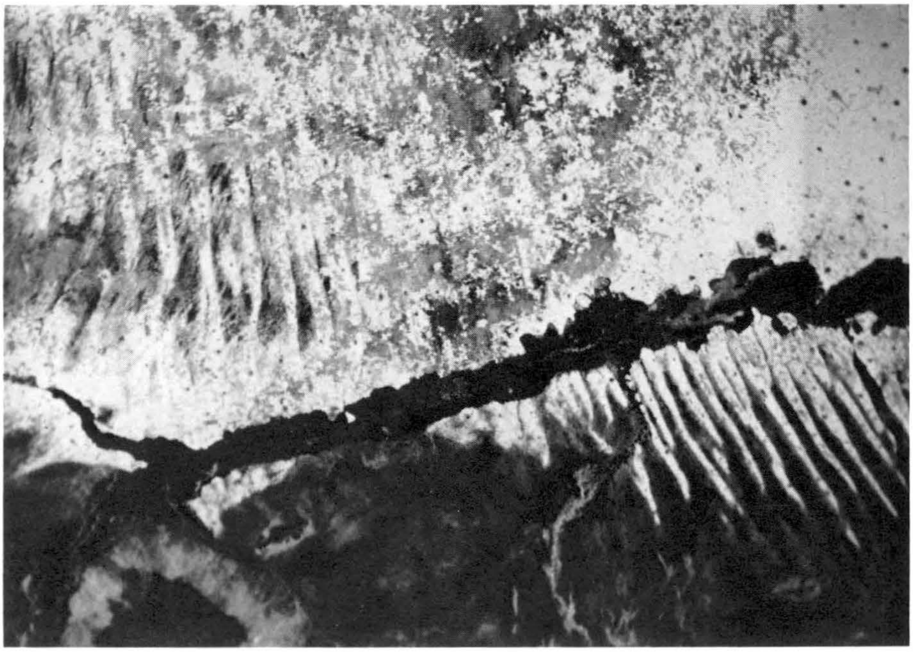

Fig. 5. Image of project area produced on digital image display from Landsat MSS band 7 data.

Fig. 6. Image of project area produced on electronic printer / plotter from Landsat MSS band 6 data. Key to prominent features in landscape: 1. Er Rahad (town); 2. Er Rahad reservoir; 3. floodplain of Wadi Abu Habl; 4. Jebel Ed Dair (granite hill); 5. upland clay plain; 6. Umm Ruwaba (town); 7. sand dunes; and 8. villages.

prepared by photographing the paper output of an electronic printer / plotter. The latter image is superior to the former in two respects: (1) it is much sharper, with the boundaries between gray levels being much clearer; and (2) the geometric or cartographic quality is far better.

It is possible to enlarge portions of a scene. Black and white images of an area to the north and west of the town of Er Rahad were produced on the digital image display from MSS band 4 and band 7 data (Fig. 7 and 8). Er Rahad is more easily located in Fig. 8. It appears as a dark spot to the northeast of the tributary of the Khor Abu Habl in the lower right-hand quadrant of the image. The white areas across the centre of Fig. 8 in general represent deep sands. Most of these sands are cultivated and are dotted with villages. The boundaries between the sands and clay plains are much more easily located in the near-infrared image (band 7) than in the image produced from reflectance in the visible green region of the spectrum (band 4).

Enlargements of Jebel Ed Dair were also produced using data from bands 4 and 7. In this case, band 7 seems to be superior to band 4 for identifying differences caused by vegetation complexes and geological features (Fig. 9 and 10).

The railway that connects Umm Ruwaba with Kosti to the east and Er Rahad to the west is distinguishable in both the enlargements from the digital display (Fig. 11 and 12) and the electronic printer / plotter (Fig. 13). Again, differences between sands and clays and variations among vegetation complexes seem to be more easily distinguished in the infrared (in this case, 0.7-0.8 μm) than in the visible (0.5-0.6 μm). The image produced on the printer / plotter (Fig. 13) is much superior to the image produced on the digital image display.

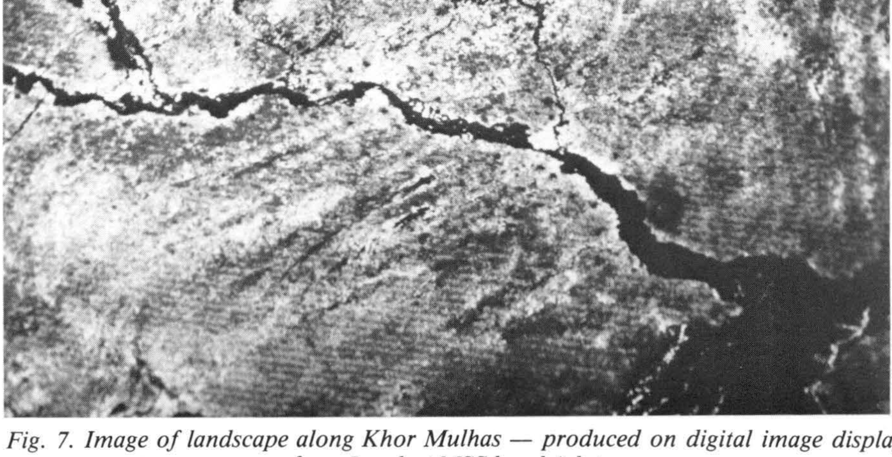

Fig. 7. Image of landscape along Khor Mulhas — produced on digital image display from Landsat MSS band 4 data.

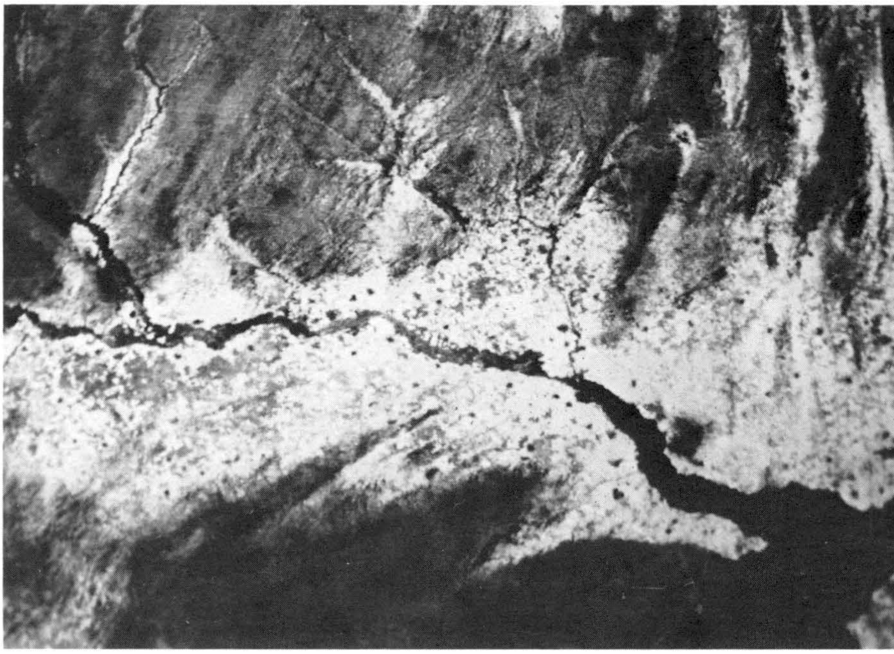

Fig. 8. Image of landscape along Khor Mulhas — produced on digital image display from Landsat MSS band 7 data.

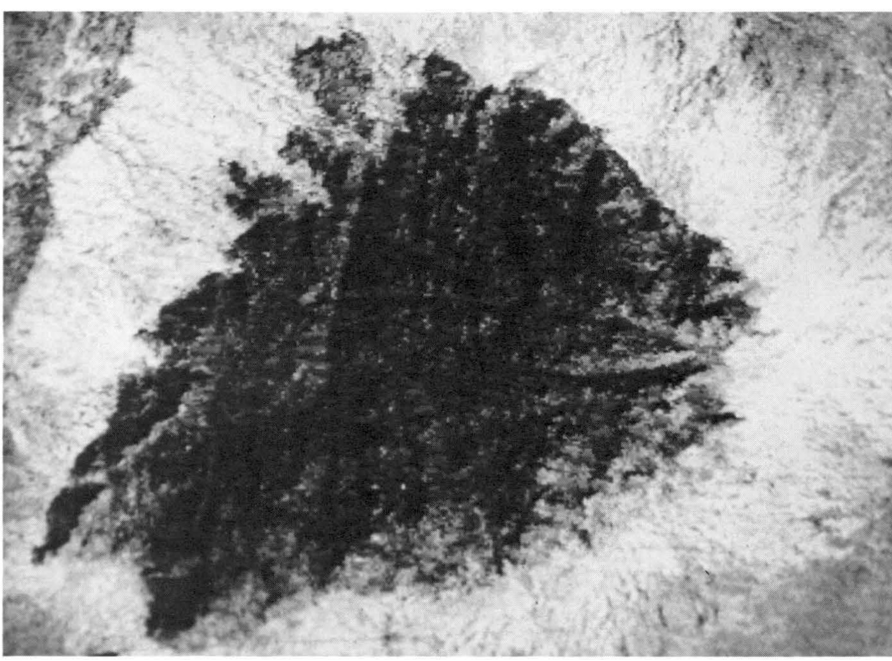

Fig. 9. Image of Jebel Ed Dair (granite hill) — produced on digital image display from Landsat MSS band 4 data.

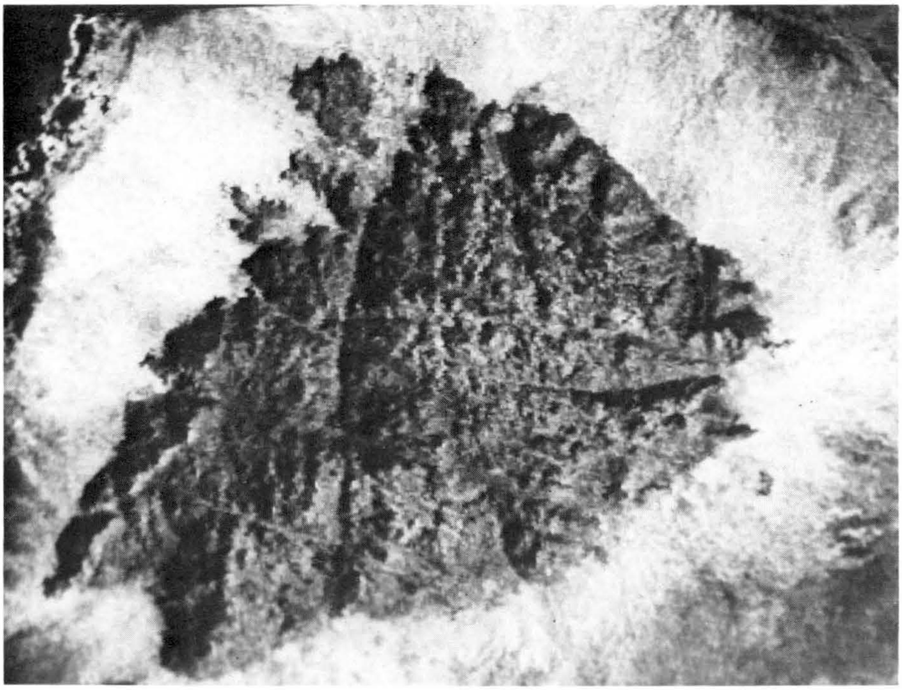

Fig. 10. Image of Jebel Ed Dair — produced on digital image display from Landsat MSS band 7 data.

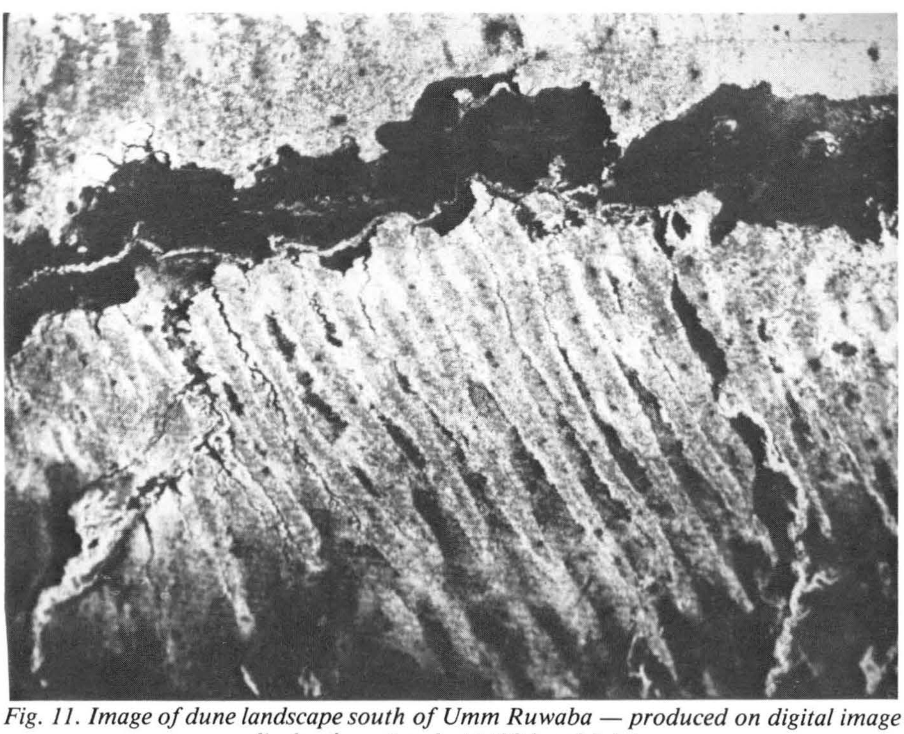

Fig. 11. Image of dune landscape south of Umm Ruwaba — produced on digital image display from Landsat MSS band 4 data.

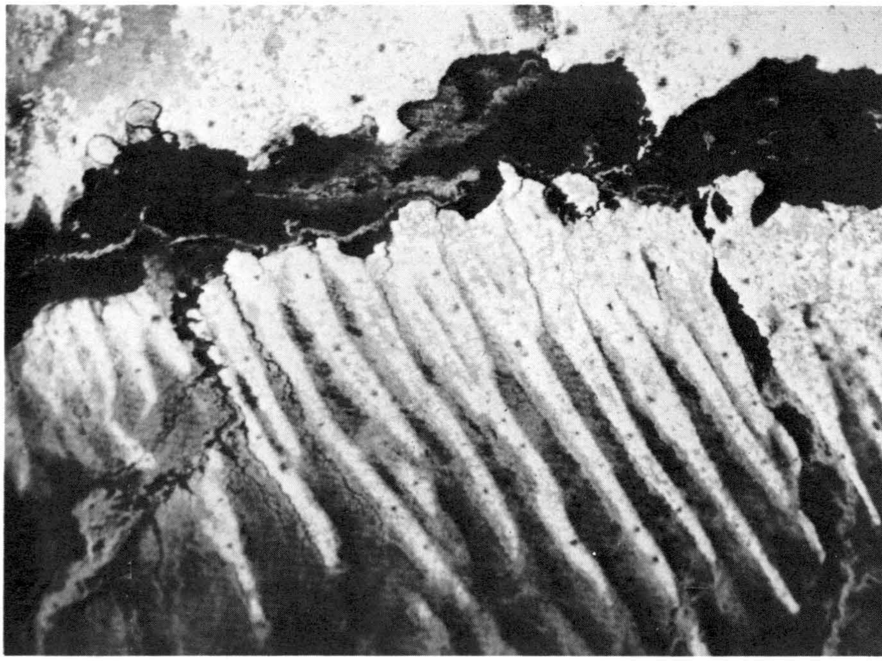

Fig. 12. Image of dune landscape south of Umm Ruwaba — produced on digital image display from Landsat MSS band 6 data.

Fig. 13. Image of dune landscape south of Umm Ruwaba — produced on electronic printer / plotter from Landsat MSS band 6 data. Key to prominent features in landscape: 1. Umm Ruwaba; 2. floodplain of the Wadi Abu Habl; 3. dunes; 4. upland clay plain; 5. railway; 6. villages; and 7. Rugeilet el Hamir (village).

Landsat Data

Eight Landsat scenes were examined, using the following criteria in the selection of multispectral-scanner data: (1) images free of clouds; (2) satellite coverage of the entire project area within a period of 4 days; (3) satellite images obtained soon after the rainy season; and (4) all four Landsat MSS bands of high radiometric quality.

False-colour composite images (scale 1:250000) and 70-mm black and white negatives for MSS bands 5 and 7 were obtained for each of the following Landsat scenes:

Landsat scene identification no.	Date of Landsat pass	Coordinates of centre of scene
1106-07365	6 Nov 72	$12^{o}49'$ N x $33^{o}34'$ E
1106-07372	6 Nov 72	$11^{o}23'$ N x $33^{o}13'$ E
1107-07424	7 Nov 72	$12^{o}49'$ N x $32^{o}06'$ E
1107-07430	7 Nov 72	$11^{o}24'$N x $31^{o}47'$E
1108-07482	8 Nov 72	$12^{o}53'$ N x $30^{o}43'$ E
1108-07484	8 Nov 72	$11^{o}27'$ N x $30^{o}22'$ E
1109-07540	9 Nov 72	$12^{o}53'$ N x $29^{o}16'$ E
1109-07543	9 Nov 72	$11^{o}27'$ N x $28^{o}55'$ E

After visual examination of these images, a computer-compatible tape for scene 1108-07482 was obtained for digital analysis and interpretation.

The Training Course

From 8 January to 25 March 1976, six Sudanese scientists attended the Remote Sensing Training Course at LARS, under the supervision of the project's consultant. Except that the crop protectionist was replaced by Hassan El Sheikh El Bashir an agricultural statistician, and the forest inventory officer was replaced by another forester Yahia I. M. Bushara, this was the same group of scientists that conducted the field mission. The main objective of this training course was to train these scientists in the use of the computer-implemented pattern recognition technique for analysis and interpretation of Landsat data obtained over the project area.

The training program included: (1) a LARS educational package, including a wide range of audio-tutorial "mini-courses" related to a basic understanding and application of remote sensing; (2) lectures and seminars on remote sensing; and (3) "hands-on" experience in computer-assisted techniques for analysis and classification of Landsat data.

On 19 March two Sudanese administrators supervising and coordinating the Remote Sensing Program joined the team at LARS. They had the opportunity to go over part of the training course and discuss with the relevant officials at LARS the future training program for Sudanese personnel.

The training period at Purdue University terminated on 25 March and the Sudanese scientists and administrators then had the opportunity to visit centres and institutes associated with other remote sensing programs (see Table 1).

Analysis and Classification

The basic course at LARS on remote sensing enabled the group to follow the computer-assisted technique for classification.[1] The steps taken to analyze and classify the area were:

(1) Production of a picture print — A picture print of the project area was produced using Landsat bands 5 (0.6-0.7 μm) and 7 (0.8-1.1 μm), using every second line and column of digital data, for the purpose of general orientation and location. Further analysis and classification were confined to scene 1108-07482 for previously stated reasons.

(2) Clustering — Four areas were chosen in this scene for clustering. These selected areas were chosen because they were representative of the frame area and the observation points from the field trip were found in or near them. They also included all the major classes expected in this scene: water, vegetation, outcrops, soil, cultivated land, and urban areas.

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[1]General information can be obtained from: National Aeronautics and Space Administration. 1972. Landsat Data Users Handbook. Greenbelt, Maryland, NASA, Goddard Space Flight Center.

Table 1. Centres and institutes visited by the Sudanese team.

Institution	Date of visit (1976)	Remarks
Goddard Space Flight Center, Greenbelt, Maryland, USA	27-30 March	The group met the director and discussed the Sudanese request for monitoring the sudd, and desert encroachment areas
U.S. Department of Agriculture, Washington, D.C., USA	31 March	Discussions of mutual interests including applications of Landsat in forestry and agricultural statistics
EROS Data Center, Sioux Falls, South Dakota, USA	1-2 April	Observations and discussions of data processing and distribution facilities and activities
International Development Research Centre, Ottawa, Canada	5-6 April	Discussion of objectives of IDRC and the nature of projects supported by IDRC
The Canadian Centre for Remote Sensing, Ottawa, Canada	7 April	Visits to and discussions of the different remote sensing data acquisition, processing, and interpretation sections
International Institute for Aerial Survey and Earth Sciences, Enschede, The Netherlands	10-13 April	Two of the group on their return trip to the Sudan had the opportunity to visit and to discuss items of mutual interest with Dutch specialists; a third member visited the Hydrology Institute in Delft, the Netherlands

Area 1: Lines 11011-1080; columns 1651-1721; interval of 1 (every line and column of data used); chosen to include Er Rahad Reservoir; expected cover types were water, vegetation, urban, and soil.

Area 2: Lines 1371-1451; columns 1861-1951; interval of 1; chosen to include Jebel Ed Dair; expected cover types were outcrops, soil, vegetation, and cultivated land.

Area 3: Lines 1081-1131; columns 2841-2941; interval of 1; lies south of Umm Ruwaba; expected cover types were soil, cultivated land, natural vegetation, and water.

Area 4: Lines 641-701; columns 1101-1191; interval of 1; included El Ain Reservoir; expected cover types were vegetation, outcrops, water, and soil.

Each area was run as a separate CLUSTER job to obtain maximum differentiation within it. In every area, four cover types were expected, so eight clusters were requested to allow for spectral subclasses.[2] A statistics file of

[2]Phillips, T. L., ed. 1973. LARSYS User's Manual. West Lafayette, Indiana, Laboratory for Applications of Remote Sensing, Purdue University.

data cards was prepared for each area, and the convergence option was set at 99.5 because this was generally expected to save time. All four bands were used for clustering in every case; the symbol set was ·,J,Z,8,O,F,Y,M.

To identify cluster classes for the four areas in terms of cover types, maximum use was made of: (1) observations from the field trip, (2) false-colour Landsat images of the project area; (3) black and white aerial-photo mosaics (1962) covering training areas 1 and 2; and (4) the spectral statistics for each cluster class.

Results of clustering area 1

The symbols were associated with cover types as follows: M water; Y tree stumps; F orchards; · light-coloured sand; Z gray sand; O, F Er Rahad town (O also villages); 8 rain-fed cultivation or green casia in moist depressions; and J plant stalks, stubble. There was some doubt, however, about the identification of the clusters represented by F and 8.

Results of clustering area 2

The following associations were made: M and Y rock (granite) sparsely covered with trees (*Terminalia, Balanites*) — it was not possible to determine if one symbol was vegetation exclusively and the other rock; F and O weathered rock and grass; Z and 8 pediment covered with *Acacia nubica, A. mellifera,* and grasses; · sand; · and J sand covered with *Cenchrus* sp.; 8 scattered patches of trees on sand; and O and 8 clay soil with *Acacia* sp. (*mellifera*?). Identification of the O, 8 combination was not positive.

Results of clustering area 3

For cluster area 3 the following associations were made: M cracking clay (dark grayish brown); · sand dunes (summit); J vegetation on sand; Y vegetation on dark clay soil (*Acacia mellifera*?); F cultivation; O trees; 8 red clay (noncracking); and Z grassland. Identification of J and Y was not positive. The following identification was based on field observations collected from 5 to 7 km north of this cluster area: 8, O, F alfisol; M vertisol; and ·, J entisol.

Results of clustering area 4

The following associations were made for cluster area 4: · sand; J grass (*Cenchrus* sp.) on sand; Z outcrop — disturbed soil; 8 vegetation — sparse trees, shrubs (*Boscia sp.*), and grass; O red clay; F cultivation; Y dense tree vegetation (shrubs) on gray clay — *Acacia nilotica;* M water. Classification for this area was: · and J grass on sand; Z outcrop or truncated soil (along drainage lines); 8 and O sparse trees — shrubs and grass on red clay; F cultivation; and Y dense tree vegetation (*Acacia nilotica*) on gray clay.

Spectral statistics were used to study and determine the validity of the cluster groupings in all cases (Tables 2-5).

Symbol M, identified as water in area 4, had larger variances than other clusters, suggesting that there might be several spectrally separable subclasses of water. To investigate this possibility a small area of lines 673-685 and columns 1179-1191 was clustered using every line and column with four clusters requested and convergence set at 100%. All four spectral bands were used. Spectral statistics were examined to determine if the four resulting spectrally separable classes were subcategories of water.

Table 2. Spectral statistics for cluster map of area 1.

Cluster class	No. of data points	Suggested cluster grouping	Band 4	Band 5	Band 6	Band 7	Symbol
				means of reflectance values			
1	723	—	49.45	76.97	81.95	35.47	·
2	1024	—	46.69	70.96	76.18	33.47	J
3	832	—	44.66	65.18	68.75	30.76	Z
4	493	—	42.17	57.90	60.23	27.03	8
5	503	—	39.02	49.59	51.80	23.11	O
6	193	—	36.01	39.38	44.13	20.11	F
7	227	—	30.14	25.63	28.78	12.32	Y
8	1046	—	26.87	18.69	12.53	3.12	M
				cluster variances			
1	—	1	8.44	9.79	7.81	1.15	—
2	—	—	6.13	6.20	6.42	1.29	—
3	—	2	4.87	5.02	6.56	1.94	—
4	—	3	5.63	8.21	7.64	2.23	—
5	—	4	5.28	7.17	9.26	3.21	—
6	—	—	6.00	30.76	12.71	5.36	—
7	—	5	5.04	8.27	25.78	10.90	—
8	—	6	4.63	5.07	6.77	2.37	—

Cluster classes 1 and 4 were not water, and had too few points to be of further interest. Cluster 3, represented by the symbol Z, appeared to be mud because the mean reflectance values compared with water (cluster 2) were dark in the visible and bright in the infrared. Quotients comparing cluster class 4 to all other clusters could not be calculated because of an inadequate number of data points.

The symbol Y, representing cluster 7 in sample area 4, was identified as dense tree vegetation, and had a large amount of variance compared with other clusters. A small area (homogeneous) was resubmitted to CLUSTER using every line and column to determine if spectrally separable subclasses of vegetation were present (run 72075001, lines 656-670, and columns 1156-1176). The area included some points around the edge from other clusters. In the new cluster analysis, four clusters were requested with convergence set at 100%. All four Landsat MSS bands were used, and the symbols O, Z, F, and Y were assigned. The spectral statistics were examined to determine if the large variance did indicate that multiple classes of spectrally separable green vegetation existed.

Cluster 1, represented by O, corresponded to data that had not been in cluster Y, that is, to border points that were not Y in the original cluster of area 4. Clusters 2, 3, and 4 (symbols Z, F, and Y, respectively) corresponded to the original cluster Y. That is, subclasses were found.

A measure of separability between clusters 2 and 3 indicated that these two clusters together were one subclass. The fourth cluster was a second

Table 3. Spectral statistics for cluster map of area 2.

Cluster class	No. of data points	Suggested cluster grouping	Band 4	Band 5	Band 6	Band 7
			means of reflectance values			
1	856	—	50.05	64.35	63.74	27.65
2	1389	—	47.72	59.45	59.74	26.36
3	1495	—	45.29	54.42	56.64	25.45
4	923	—	46.95	46.07	52.94	24.27
5	561	—	39.50	42.67	47.93	22.38
6	799	—	35.62	34.72	43.14	20.53
7	867	—	32.00	28.31	38.16	18.43
8	481	—	28.87	23.99	31.12	14.95
			cluster variances			
1	—	1	4.69	4.63	5.98	1.40
2	—	—	2.85	2.80	3.76	0.87
3	—	2	2.43	2.99	3.23	0.89
4	—	—	2.16	3.71	4.32	1.38
5	—	3	2.66	5.90	3.98	1.31
6	—	4	2.23	5.36	4.78	1.57
7	—	5	2.87	5.70	6.40	1.82
8	—	—	2.53	6.08	8.96	3.20

subclass. These subclasses may correspond to differences in species. More work was done on identifying the eight clusters in each of the four sample areas (Tables 6 and 7).

An algorithm known as MERGESTATISTICS was used to combine the sets of statistics from the four study areas. This exercise generated a new statistics set that was used for further analysis and interpretation. The merging of the statistics sets of the four areas suggested that it would be appropriate to group the 32 cluster classes into 20 classes (Table 8).

Another computer program was used to examine quantitatively the spectral separability of the 20 classes. Known as XSEPARABILITY, this algorithm suggested that the 20 classes could be further pooled into 12 spectral classes (Table 9).

In an attempt to provide a visual presentation of the different classifications, a variety of sets of symbols were used to portray both the 20- and 12-class classifications (Table 9). This technique may be used for enhancing specific features of interest. For example, it is useful at times to print a single symbol representing a particular feature, perhaps "S" for sand, and delete all other classes.

Spectral statistics for the 12 classes were used to classify an area of approximately 10000 square kilometres that included all four training areas. The first classification was produced by using only every tenth line and column of data.

These classifications were then examined by the computer to determine how many points did not fall into the 12 spectral training classes. This analysis

Table 4. Spectral statistics for cluster map of area 3.

Cluster class	No. of data points	Suggested cluster grouping	Band 4	Band 5	Band 6	Band 7
				means of reflectance values		
1	892	—	46.24	70.14	77.71	34.15
2	694	—	45.00	64.71	69.77	31.31
3	252	—	52.67	64.12	62.78	27.54
4	716	—	45.47	59.18	60.31	26.67
5	724	—	44.84	53.06	54.54	24.34
6	827	—	42.52	46.86	49.26	22.24
7	469	—	39.07	40.14	44.23	20.10
8	577	—	35.39	33.41	33.92	15.13
				cluster variances		
1	—	1	2.60	10.76	7.65	1.52
2	—	—	2.96	5.13	7.97	2.66
3	—	2	10.01	5.90	6.27	1.46
4	—	—	5.71	5.08	5.94	1.74
5	—	3	3.99	4.85	4.43	1.05
6	—	4	3.00	4.09	3.82	0.99
7	—	—	2.69	8.00	6.21	1.82
8	—	5	4.04	7.55	6.42	1.66

indicated that seven groups of data points had been segregated. In other words, the cover types present in these areas were spectrally different from the cover types represented by the 12 training classes.

The next step was to inspect these seven thresholded areas in an attempt to characterize or identify the surface cover. Using all four spectral bands, a preliminary identification of the cover types (bare soil, vegetation, water) was made. The data were then plotted in histograms to examine their variability, which revealed that three of the seven areas were heterogeneous, that is, they had large standard deviations from the mean spectral reflectance values.

These three heterogeneous classes were submitted for separate cluster analysis with eight cluster classes requested. The areas that were clustered were in fact larger than those originally thresholded, indicating that data points from the other training classes were now being included. By delineating the thresholded areas in the cluster map, those clusters not having points inside these areas could be deleted. In this manner, five of these eight new clusters were eliminated. Statistics sets were prepared for the three remaining cluster classes and for the four thresholded areas that were homogeneous.

The statistics sets for these seven classes were then merged with the sets from the 12 training classes into a 30-class deck. Through a series of separability and merging manipulations these 30 classes were reduced to 26, to 20, and finally to 13 classes.

Final products displaying the 13 classes included computer printouts, a colour-coded classification made on a digital image display (television

Table 5. Spectral statistics for cluster map of area 4.

Cluster class	No. of data points	Suggested cluster grouping	Band 4	Band 5	Band 6	Band 7
			means of reflectance values			
1	306	—	54.46	70.46	68.98	29.65
2	693	—	51.74	64.03	63.79	27.91
3	918	—	49.52	58.68	59.12	26.10
4	1327	—	47.23	53.75	55.21	24.64
5	1260	—	44.62	49.04	51.93	23.65
6	292	—	40.34	41.29	48.60	22.65
7	498	—	33.11	28.06	42.97	21.22
8	257	—	45.26	44.05	28.04	5.93
			cluster variances			
1	—	1	4.35	9.52	5.96	1.19
2	—	—	4.89	3.32	4.78	1.06
3	—	2	3.70	3.07	4.01	0.93
4	—	3	2.43	2.96	3.03	0.79
5	—	—	2.32	3.28	3.22	0.82
6	—	4	4.64	11.17	8.11	3.35
7	—	5	7.04	15.45	8.97	6.80
8	—	6	14.06	37.89	15.55	5.46

monitor), a print from a Varian electronic printer / plotter, and a geometrically correct colour-coded map produced by a firm with specialized colour-printing equipment. This was the final stage of the training program at LARS.

Examples of Classification Results

Classification results from the digital analysis of Landsat MSS data can be presented in several formats and in a wide range of scales. One of the most dramatic methods is a colour-coded classification produced at a scale of 1:50000 (see frontispiece). The method used in the production of these colour maps retains the geometric fidelity (cartographic quality) of the digital data on the magnetic tape.

Less dramatic but equally useful formats may be produced by much less expensive methods (Fig. 14-17). The first two examples (Fig. 14, 15) represent classification results that were produced on a high-speed line printer driven by the computer. These examples have been reduced photographically from the original scale of 1:25000. This method also does a good job of transferring the cartographic quality of the image from the tape to the computer printout.

The next two examples (Fig. 16 and 17) appear at the scale as originally printed (1:25000). At the time of reformatting and geometric correction of the Landsat MSS data used in this study, the request was made for digital data at a scale of 1:25000. Almost in the centre of Fig. 16 and 17 is a village, which can be easily delineated and mapped. (The key for the class descriptions of the symbols and patterns is presented in Table 10.) The village is located on the southern extension of a sand dune south of the Khor Abu Habl, to the northeast of Jebel Ed Dair, and the northwest of Jebel Dumbeir.

These examples illustrate two inexpensive methods for comparison of black and white classification formats. The first (Fig. 16) is produced on a line printer; the second (Fig. 17) on an electronic printer / plotter. With the former the analyst is limited to the symbols available on the keyboard or line printer. With the latter, the analyst is limited mainly by his imagination in the design of patterns he wishes to use to represent specific classes.

Final Field Check

The team conducted the final field evaluation mission during the period 25-29 November 1976. The timing coincided well with the date of acquisition in 1972 of the Landsat data used in the study. Both ground and aerial observations were made. Ground observations were made specifically around areas that were readily located and identified in the Landsat data, and were accessible. The principal geographical areas for field observations (Fig. 18) included the areas surrounding Banno reservoir, El Ain reservoir, Er Rahad reservoir, Abu Habl floodplain, Jebel Ed Dair, and Nowa railway station. During the field evaluation the following materials were used: (1) a colour-coded classification (scale 1:48000); (2) a colour-coded classification (scale 1:240000); (3) a computer printout of the classification (scale 1:240000);

Table 6. Interpretation of spectral classes in the four sample areas.

	Landscape features			
Symbol	Area 1	Area 2	Area 3	Area 4
.	white sand	sand (2)	sand (3)	sand (4)
J	crop stalks	grass (2)	grass (3,1)	grass (4)
Z	gray sand	noncracking clay	grass (3,2)	truncated soil
8	rain cultivation	scattered patches of trees	noncracking red clay	sparse trees and shrubs (*Boscia* sp.)
O	village	clay soil with *A. mellifera*	trees	red clay
F	orchards	trees (*Terminalia*) on weathered rock	cultivated land (3)	cultivated land (4)
M	water	granite (2)	cracking clay	water
Y	tree stumps	*Terminalia, Balanites,* and *Boswellia* sp. (gafal) on granite	*A. mellifera* on dark clay	sunot tree (*A. nilotica*)

Table 7. Observation data and statistics used to rationalize merging of 32 spectral classes to 20 classes (column 3).

Class number	Class symbol	New class	No. of data points	Identification using minimal ground observation data	Identification aided by current colour photography of sample areas of landscape
1	A	1	723	white sand	white sand
2	B	2	1024	crop residue	crop residue on sand
17	Q	-	892	sand (3)	sand (3)
3	C	3	832	gray sand	brownish sand
18	R	-	694	grass (3,1)	dry grass (3,1)
4	D	4	493	rain-fed cultivated land	rain-fed cultivated land
20	T	-	716	noncracking red clay	trees (*A. mellifera*) on noncracking red clay
5	E	5	503	village	village
6	F	6	193	orchards	orchards
7	G	7	226	tree stumps	dense green *Tamarix* sp. (safsaf) on water
8	H	8	1046	water	water
9	I	9	856	sand (2)	gravelly heavy loam, dark red
19	S	-	252	grass (3,2)	dry grass (3,2)
26	Z	-	693	grass (4)	dry grass (4)
10	J	10	1389	grass (2)	dry grass (2)
27	$	-	918	truncated soil	noncracking yellowish-red clay
11	K	11	1495	noncracking clay	noncracking clay with grasses
21	U	-	724	trees	trees (*A. mellifera*) on red clay
28	+	-	1327	sparse trees and shrubs (*Boscia* sp.)	yellow-red noncracking clay, grass
14	N	12	799	trees (*Terminalia* sp.) on weathered rock	trees (*Terminalia* sp.) on weathered rock
15	O	13	867	*Terminalia, Balanites,* and *Boswellia* sp. on granite	*Terminalia, Balanites,* and *Boswellia* sp. on granite
16	P	14	481	granite (2)	granite covered with vegetation
12	L	15	923	scattered patches of trees	scattered patches of trees
22	V	-	827	cultivated land (3)	cultivated land (3)
29	.	-	1260	red clay	*A. mellifera,* shrubs, and dry grass.
13	M	16	561	clay soil with *A. mellifera*	*A. mellifera* on heavy loam
23	W	-	469	*A. mellifera* on dark clay	*A. mellifera* on dark clay
30	—	-	292	cultivated land (4)	cultivated land (4)
24	X	17	577	dark cracking clay	dark grayish-brown cracking clay
25	Y	18	306	sand (4)	sand (4)
31	/	19	498	*A. nilotica* (sunot) trees	*A. nilotica* (sunot) trees
32	=	20	257	water (4)	water (4)

(4) a false-colour image of the area (scale 1:240000); and (5) survey sheets (scale 1:250000).

Aerial reconnaissance covered most of the project area. Beginning at El Obeid, the flight path covered Banno reservoir, El Ain reservoir, Er Rahad

Table 8. Merging of 32 spectral classes into 20 spectrally separable classes.

Old class	New class	New symbol	Class name
1	1	A	white sand
2,17	2	B	sand, crop residue
3,18	3	C	bare red sand, dense grass
4,20	4	D	cultivated land, *A. mellifera* on red clay
5	5	E	village
6	6	F	orchards
7	7	G	*Tamarix* sp. (safsaf) on water
8	8	H	water
9,19,26	9	I	dry grass on hard red loam
10,27	10	J	dry grass on noncracking clay
11,21,28	11	K	*A. mellifera,* grass on noncracking clay
14	12	L	*Terminalia* sp. on weathered rock
15	13	M	*Terminalia, Balanites,* and *Boswellia* on granite
16	14	N	granite, vegetation
12,22,29	15	O	*A. mellifera,* grass, cultivated land
13,23,30	16	P	*A. mellifera,* cultivated loamy clay
24	17	Q	dry grass, bare red clay
25	18	R	sand (4)
31	19	S	*A. nilotica* (sunot)
32	20	T	water (4)

Table 9. Suggested grouping of 20 spectral classes into 12 classes.

Old class	New class	Symbol sets 1	2	3	4	Class name
1,2	1	.	.	-	.	sand
3	2	+	+	.	+	sand (2)
4,10	3	-	S	I	S	vegetation on red noncracking clay
5,15	4	I	I	S	'	sparse vegetation
6,12,16	5	*	*	X	*	trees
7,14	6	Z	$	Z	X	dense vegetation
8	7	S	W	W	W	water (2)
9,18	8	H	-	O	-	bare soil
11	9	O	=	=	O	vegetation on clay
13,19	10	F	8	F	8	trees (2)
17	11	$	/	$	$	vertisols
20	12	M	M	M	M	water

Table 10. Key to classes in Fig. 16 and 17 and the colour-coded classification.

Classification results			
Symbol (Fig. 16)	Pattern (Fig. 17)	Colour (frontispiece)	Description
O		dark blue	water
8		medium blue	water (and floating wood)
-		light blue	sparse vegetation on truncated upland clay
·		white	sand
·		tan	dark sand
·		yellow	cultivated crops or mixed grass species on sand
S		light green	sparse tree vegetation on vertisols
F		blue green	sparse tree vegetation on vertisols
M		dark green	vertisols (dark swelling clays in floodplain)
+		rust	very sparse vegetation on upland clays
Z		orange	sparse vegetation on upland clays
I		red	trees (dense on clays)
*		black	dense woody vegetation, trees in floodplain

reservoir, Abu Habl floodplain, Jebel Ed Dair, the town of El Simeih, the town of Um Ruwaba, and Shirkeila village.

It was found that the classification was generally satisfactory. Water bodies, seasonal water courses, the Jebel Ed Dair outcrop covered with vegetation, and sand (sand dunes and sand sheets) were classified and identified correctly. However, a few of the features were lost in the classification, e.g. some urban areas (El Obeid), railroads, and bare outcrops. This may be due to the fact that there was insufficient ground observation data to select representative training sets for computer-implemented analysis.

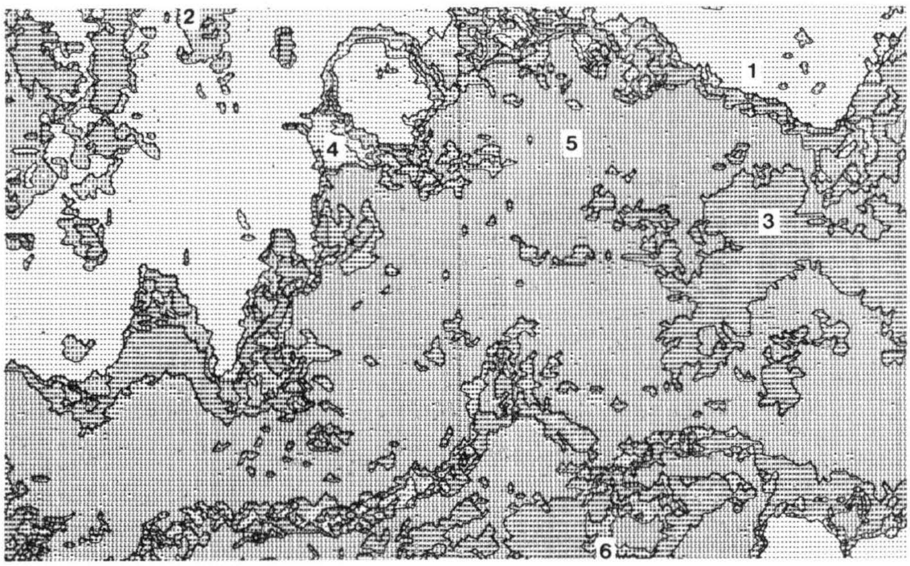

Fig. 14. Computer-implemented classification of landscape around Abu Hamra (km 510 on railway). Key to classification: 1. sand, sand sheet; 2. vegetation / upland clay complex; 3. dense vegetation on vertisols (floodplain); 4. bare soil, uplands; 5. vertisols, dark swelling clays; and 6. vertisols, wet.

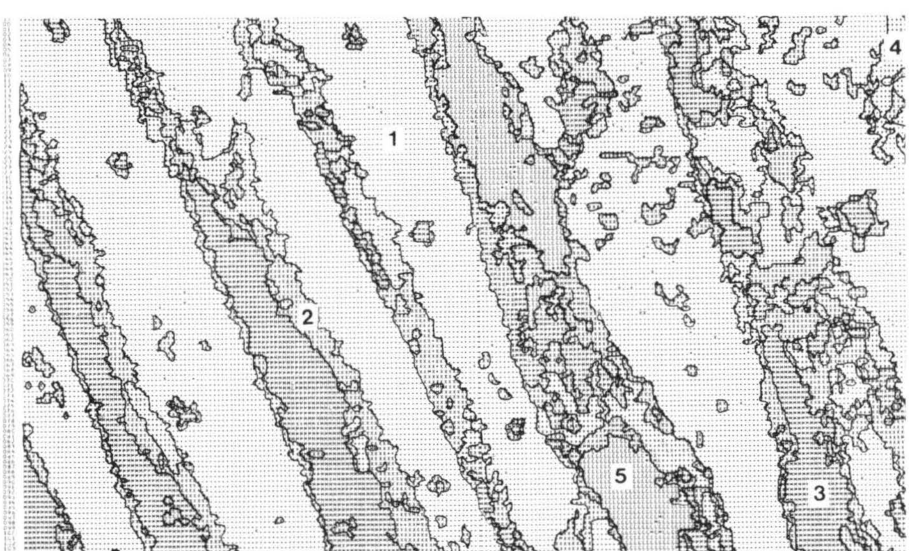

Fig. 15. Computer-implemented classification of dune landscape south of Umm Ruwaba: 1. sand, sand sheet; 2. vegetation / upland clay complex; 3. dense vegetation on vertisols (floodplain); 4. bare soil, upland; 5. vertisols, dark swelling clays; and 6. vertisols, wet.

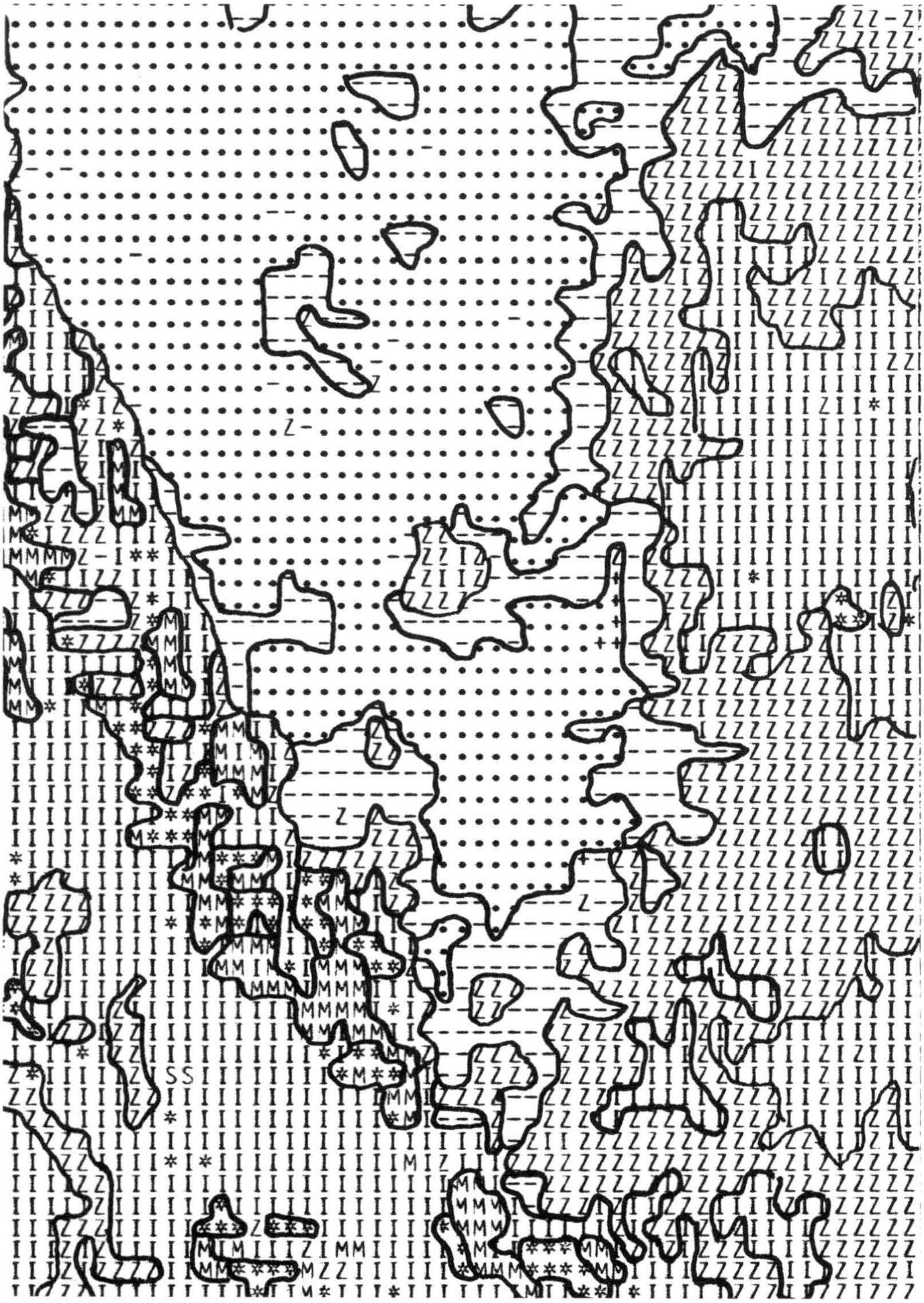

Fig. 16. Computer-implemented classification of landscape northeast of Jebel Ed Dair and northwest of Jebel Dumbeir — produced on line printer.

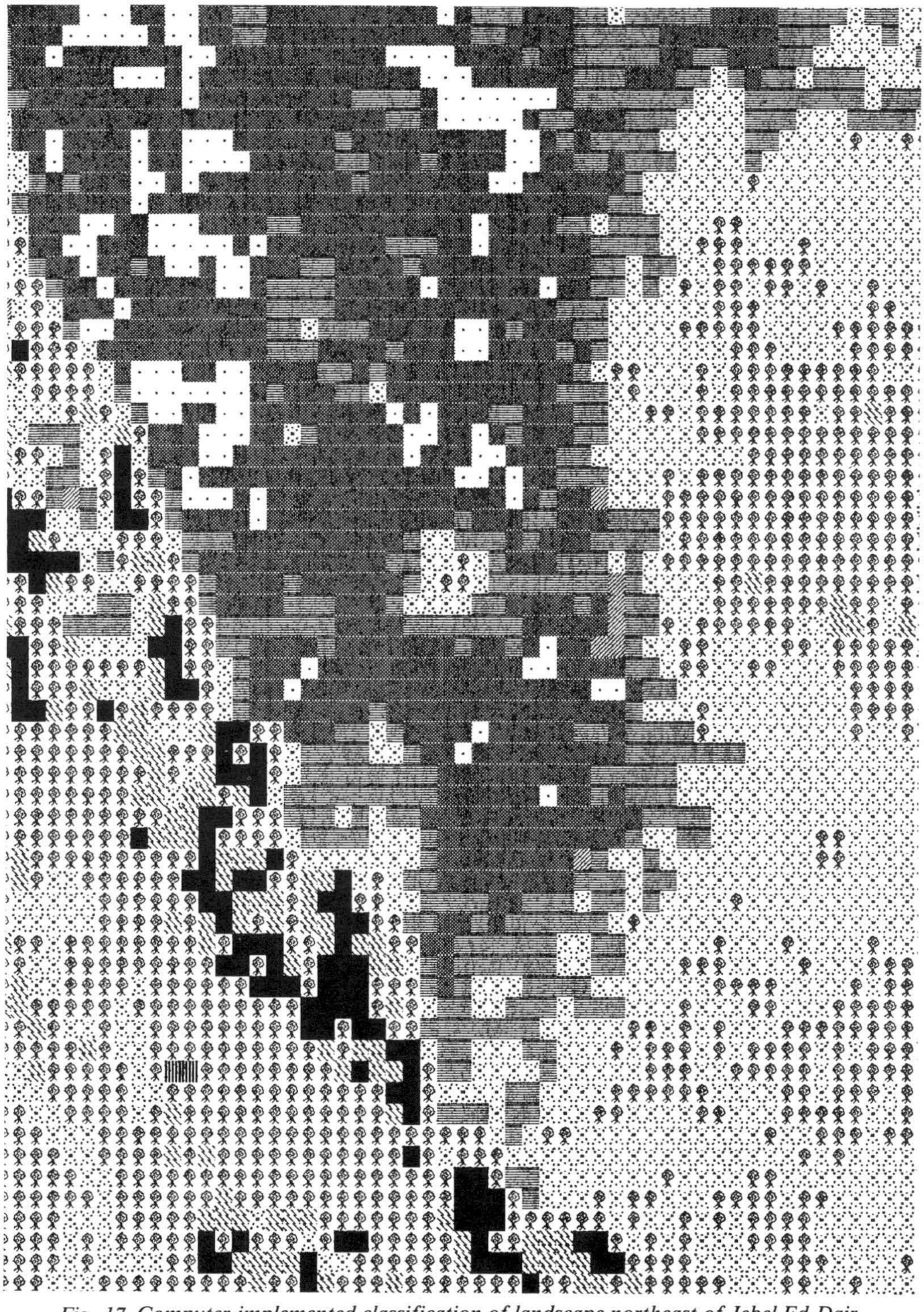

Fig. 17. Computer-implemented classification of landscape northeast of Jebel Ed Dair and northwest of Jebel Dumbeir — produced on electronic printer / plotter.

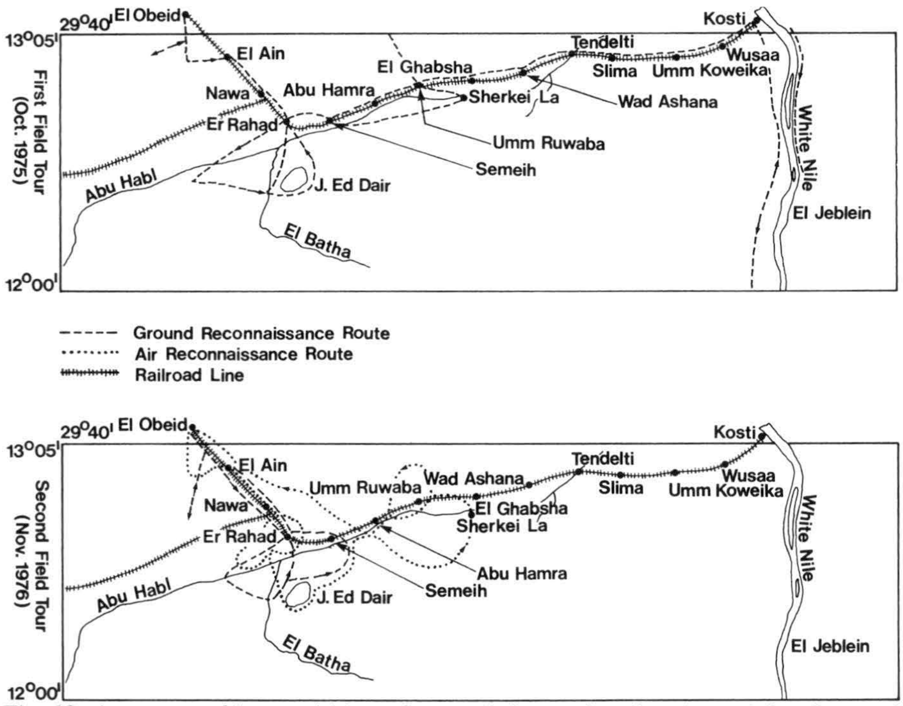

Fig. 18. Area covered in acquisition of ground observation data by aerial and ground reconnaissance.

Visual Classification

To meet the third objective of the project, that is, produce maps of the natural resources, a visual interpretation and classification of the colour composite (scale 1:250000) of scene 1108-07482 was made. A topographic survey map at the same scale provided supplemental data for interpretation, while previously obtained ground observations and experience in the study area were also valuable. Digital analysis and classification covered the central portion of the frame; whereas, visual analysis was completed for the entire frame, which covered the area approximately between latitudes $12^{\circ}15'$N and $13^{\circ}45'$N and longitudes $30^{\circ}00'$E and $31^{\circ}30'$E.

Evaluation

Training

The training program followed by the Remote Sensing Unit of the Sudan was unique in that it was the first program in the country to provide training opportunities to a number of scientists from different disciplines. As such, it laid the foundation for regular application of remote-sensing techniques in natural-resource surveys. This nucleus of trained scientists, through practical field work and advanced training and experience, has made an invaluable contribution to planning the future of the Remote Sensing Unit. The experience gained during the project's training program clearly indicates that the application of remote sensing to natural resource surveys in the Sudan is feasible.

The major time and emphasis during the training in the United States involved the digital analysis of Landsat MSS data. Following the training period at LARS, the short tour of other centres in the United States, Canada, and the Netherlands enabled the trainees to become acquainted with other methods and equipment used in the processing and interpretation of Landsat images.

In weighing the advantages and disadvantages of visual and machine processing of Landsat data in the Sudan, the following factors must be seriously considered: (1) the hardware (computer) is not readily available at this time for this kind of machine processing; (2) computers are expensive to purchase and operate, and specialized operators and physical facilities are required; (3) for computer processing to be economical, there must be a sufficient volume of work; and (4) accuracy of analysis by both visual and machine methods is greatly dependent upon the availability of good ground observation data — training sets that are representative of all features to be identified must be spectrally separable if classes are to be delineated by machine processing.

Where appropriate computer facilities are available, computer-implemented pattern recognition techniques provide several advantages: (1) they provide rapid analysis of data from large areas; (2) if data sets representative of earth surface features of interest can be identified, excellent classifications can be obtained with a minimum of ground observation data; and (3) digital analysis provides quantitative results that can be related to area measurements and the spectral separability of features of interest.

Classification of Landsat Data

The final classification was generally satisfactory and useful because information was acquired about an area for which thematic maps with such detail did not exist, and, in fact, two thematic maps were produced as a result of the study. However, the final classification might have been more detailed, and possibly more accurate, had it been possible to: (1) obtain an adequate set of ground observations representative of the features or classes of interest in the landscape; (2) make ground observations at approximately the same time as the Landsat MSS data acquisition; and (3) establish more check points in the scene that could be easily identified and precisely located on the ground and in the Landsat MSS data.

One of the difficulties encountered in this study is common in many areas of the world, i.e. the difficulty of traversing the study area at ground level. Deep sands, wet areas, and lack and inadequacy of roads make it extremely difficult and expensive to carry out an effective ground observation mission.

The Landsat data used in this study were acquired during satellite passes in November 1972. The initial field tour of the area was made in late October and early November 1975, the final field tour and evaluation in November 1976. Although it is highly probable that no major changes occurred in the landscape of the project area during this period, the practice of shifting cultivation, especially on the deep sands, poses problems in the analysis and interpretation of land-use patterns.

The results of the final classification have shown that it is relatively easy to identify and map gross features such as land systems, large forested areas, sand dunes, and water bodies. Major difficulties were encountered only in the identification of small areas of spectrally separable features for which little or no precise ground observation data were available. A case in point is that in the early digital analysis as many as 32 spectrally separable classes were produced. Because insufficient ground observation data were available, it was impossible to determine or explain how subtle differences in soils, vegetation, soil-vegetation complexes, or other surface features were related to this spectral separability. Lack of understanding of these relationships relegates the analysis to merge classes until the number and characteristics of spectrally separable classes can be related to known features or combinations of features in the landscape.

Recommendations

As a result of the evaluation and critical study of remote sensing technology, the study team proposed:

(1) that the multidisciplinary effort of the Remote Sensing Unit be expanded and strengthened. The Sudan's 6-year Development Plan (July 1977 to July 1983) includes a request for $203 630 in local and foreign currency to support a comprehensive program of natural-resource surveys. This request includes support for training, equipment, and facilities. An important aspect of this recommendation is the need to solicit technical and financial support from abroad;

(2) that funds be made available for further training of Sudanese scientists in visual interpretation techniques;

(3) that close cooperation and collaboration be developed among the various Sudanese government agencies that have responsibilities for the development, management, and conservation of the country's natural resources. As this recommendation is implemented, it might be appropriate for the different cooperating agencies to assign some of their specialized staff to the Remote Sensing Unit;

(4) that the analytical equipment that has been selected be acquired by the Sudan as soon as possible;

(5) that closer communications and professional contacts be practiced regularly among Sudanese specialists and officials in international institutions sharing common interests. These contacts should be strengthened through exchange visits, participation in seminars, exchange of publications, contributions to scientific journals, and attendance at training courses;

(6) that a report should be published to strengthen the understanding and use of remote sensing technology in the Sudan and elsewhere.